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Simulation of a Climatology for Leaf Wetness Duration in Field Corn

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and
T.J. Gillespie

ATMOSPHERIC ENVIRONMENT SERVICE

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Simulation of a Climatology for Leaf Wetness Duration in Field Corn

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ABSTRACT:

Computer models of the evaporation of dew and the drying of water drops on plant leaves were combined to simulate leaf wetness duration at a depth within a corn canopy that is critical for the onset of disease. The models, originally developed by Pedro and Gillespie (1982) and Zhang and Gillespie (1990) for use in the field, were adapted to run on hourly climate observations over a five month period (May - September) at different locations in Canada. The models were used to compute the probability of particular episodes occurring in any month, the return period of extreme episodes and the average temperature associated with different lengths of leaf-wetness duration. The formation of dew was inconsequential in all but a few of the episodes of leaf wetness. The longer episodes resulted from precipitation followed by slow evaporation of rain drops.

The simulation did not exhibit any observable pattern between average temperature and the length of surface wetness duration. However, analyses of leaf wetness duration exceeding one day and of the synoptic patterns of extreme episodes provided evidence that leaf wetness varies both seasonally and geographically. These analyses further indicated that at the depth used in this study, only the simulation of drop evaporation is necessary for a larger-scale synoptic climatology and spatial analysis of leaf wetness duration.

RÉSUMÉ:

Pour simuler la durée de l'humidité des feuilles á une profondeur du couvert de maïs critique pour l'apparition de la maladie, on a combiné des modèles informatiques de l'évaporation de la rosée et du séchage des gouttelettes d'eau sur les feuilles des plantes. Conçus á l'origine pour le terrain par Pedro et Gillespie (1982) et par Zhang et Gillespie (1990), ces modèles ont été adapté. Ils peuvent donc fonctionner avec des observations climatologiques horaires pendent cinq mois (mai á septembre) á divers endroits du Canada. On s'est servi de ces modèles pour calculer la probabilité de certains épisodes á tout mois donné la période de récurrence des épisodes á extrêmes at la température moyenne liée á diverses durée de l'humidité des feuilles. La formation de rosée était sans importance, sauf dans quelques épisodes de l'humidité des feuilles. Les épisodes les plus longs découlaient de précipitations suivies d'une lent évaporation des gouttelettes de pluie.

La simulation n'a pas révélé de configuration observable entre la température moyenne at la durée de l'humidité des feuilles. Toutefois, en analysant la durée de l'humidité des feuilles supérieure á une journée at la configuration synoptique des épisodes extrêmes, on a établi que l'humidité des feuilles varie suivant la saison at le lieu. En outre, ces analyses ont

indiqué qu'à la profondeur utilisée dans l'étude seule la simulation de l'évaporation des gouttelettes est nécessaire à une climatologie synoptique à plus grande échelle et à l'analyse spatiale de la durée de l'humidité des feuilles.

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SIMULATION OF A CLIMATOLOGY FOR LEAF WETNESS DURATION IN FIELD CORN

1. INTRODUCTION

Data on leaf wetness duration is important in the control of certain foliar diseases (Van der Wal, 1978). Observations on leaf wetness are not routinely collected due to lack of equipment (Pedro and Gillespie, 1982). Pedro and Gillespie (1982) developed a computer model that simulated the length of time required for dew to evaporate from a leaf and Zhang and Gillespie (1990) have developed a similar model for rain drops. Although these models were developed for real time applications on individual plants, they were combined and adapted for a climatological assessment at six locations in the corn growing area of Canada. At deeper levels in the canopy, (18 - 25% of crop height) which are more prone to the onset of disease, the performance of the simulation model for these locations highlighted the significance of precipitation and evaporation on leaf wetness duration. At these depths the formation of dew was not important for critical durations of leaf wetness.

The dew model was based on an energy balance of an individual leaf, computed as the difference between leaf and air temperature. The energy balance was used to calculate the temperature of the leaf which in turn was used in calculating the latent heat flux. The second model simulates the length of time required for a drop to evaporate from the surface of a leaf. The model is based on the Penman combination equation (Campbell, 1977) adapted for the curved surface of a droplet. Both the dew and the drop model require an estimate of incoming shortwave solar radiation. Incoming solar radiation was estimated using the Atmospheric Environment Service (AES) solar radiation model which incorporates the McMaster University (MAC) cloud-layer model (Davies et al, 1984) for estimating global irradiance on a horizontal surface (Morris and Skinner, 1990). All three models were driven with standard hourly weather station data.

The results obtained indicated no pattern between the length of time that the leaf was wet (an episode) and the average temperature of an episode. A regional variation emerged when the probabilities of multiple occurrences of leaf wetness episodes greater than or equal to twenty-four hours or more were computed on a monthly basis. The Gumbel distribution was utilized to calculate the return period of extreme periods of leaf wetness. The severity of the return values exhibited a regional variation similar to that which was found with the computation of the probabilities of each episode. Major synoptic features were identified for extreme episodes of three days duration or greater. Most of the longer episodes of leaf wetness were associated with a deepening of the upper trough which resulted in

a cut-off low, and these episodes were invariably terminated by the establishment of a surface high.

2. CLIMATE, WEATHER, AND PLANT DISEASE

The relations between weather and plant disease are well established (Shaner, 1981). This is due in part to the fact that meteorological variables are monitored more widely than other important factors associated with plant disease. Most disease development is affected by temperature and for some it is the only important information needed to forecast infection (Hodges, 1969). Rainfall and dew are also valuable and are often monitored in conjunction with temperature. Rainfall alone was highly correlated with vector numbers of the maize streak virus in Zimbabwe (Thresh, 1974). Temperature data in combination with relative humidity were employed to predict the development of corn leaf blight (Hyre, 1970).

Most studies of climate and plant disease have focused on the day-to-day variation in weather rather than year-to-year climatic variability. Not surprisingly, there are very few studies of how climatic variability affects plant disease, and these are reviewed in Coakley (1988). Climatological studies are necessary to examine intergenerational development of pathogens, geographical distributions of diseases, areas prone to disease, dispersal of a pathogen or vector with respect to synoptic scale movement, the evolution of host-pathogen interactions and the long term control of a disease (Coakley, 1988). Perhaps it is due to the advent of possible global warming that there are increased concerns about the role of climate in determining the geographic areas that are suitable to specific crops, vectors, and pathogens.

There have been a number of references to the contribution of leaf wetness duration in the onset of plant disease (Davis, 1957; Van der Wal, 1978; Thompson, 1981; Royle and Butler, 1986; Knudson and Hudler, 1987). Most fungal diseases require a specific length of leaf wetness in order to complete the cycle of infection and produce new spores. While the acquisition of real-time knowledge would be useful for reducing costly chemical sprays, a climatology of leaf wetness would delimit those areas most prone to fungal diseases. This geographic data base could in turn be used for the optimal location of monitoring stations which are part of a strategy for preventing epidemics (Young, Prescott, and Saari, 1978).

Unfortunately, an appropriate spatio-temporal data base of leaf wetness duration does not exist. Since leaf wetness duration is dependent on other meteorological and morphological variables (i.e, temperature, radiation, wind speed, height of the canopy, the type of crop), various attempts have been made to estimate it with empirical and simulation models. With the

exception of Thompson (1981), models of leaf wetness duration either focused on the evaporation of dew or the evaporation of droplets, although Thompson does not adapt his model for the geometry of a drop. Thompson developed an energy balance model that yields the rate of heat loss and evaporation at different layers of a crop. The model used many of the same physical principles that were found in Zhang and Gillespie (1990), however Thompson did not verify his simulations with field data from a crop. Other attempts at estimating leaf wetness are reviewed in Pedro and Gillespie (1982).

3. MODELLING THE EVAPORATION OF DROPLETS FROM THE LEAF'S SURFACE

Zhang and Gillespie (1990) developed and field tested a model to estimate wetness duration for drops placed on shaded maize leaves. The model was based on the Penman combination equation

$$LE = [sRn + \rho C_p(VPD)/r_b]/(s+\gamma)$$

where LE is evaporation, Rn is net radiation, ρC_p is the volumetric heat capacity of air (1200 J/cm^3 °C), r_b is the boundary layer resistance, s is the slope of the saturated vapour pressure curve, VPD is the vapour pressure deficit and γ is the psychrometric constant ($6.4309*10^{-4}$). This equation was altered to calculate the rate of evaporation of slow-drying droplets from heat and mass transfer theory for hemispheroids. This model, originally designed to run on microclimatic observations (Barr and Gillespie, 1987), has been simplified to run on weather station data. The model predicts the evaporation of droplets deep in the canopy.

Penman's combination equation was rewritten in terms of watts for convenience.

$$E_w = F_w[sRn_d/F_h + \rho C_p\ VPD]/(1+sF_w/F_h)$$

where

$F_h = A_s/r_{bt} + A_b/r_{bb}$ is the heat factor and,

$F_w = A_s/\gamma r_w$ is the water factor.

In the equation for E_w, Rn_d is the net radiation at the drop, A_s is the upward facing surface area of the drop, and A_b is the area of the drop's base. The boundary layer resistances for heat transfer from the top and bottom of the drop are represented by r_{bt} and r_{bb} respectively, and r_w represents the boundary layer resistance for water vapour transfer.

The VPD was computed as the difference between the saturated vapour pressures for the weather station dry bulb (e_{DRY}) and dew point (e_{DEW}) temperatures respectively:

$$\text{where } e_{DRY} = 6.1078 \exp(17.269*T_a)/(T_a + 237.3)$$

$$\text{and } e_{DEW} = 6.1078 \exp(17.269*T_{DEW})/(T_{DEW} + 237.3)$$

where T_a and T_{DEW} represent the dry bulb and dew point temperatures. The slope of the saturation vapour pressure curve, s was approximated from the same parameters

$$s = [(6.1078 * 17.269 * 237.3)/(T_a + 237.3)^2] * \exp((17.269* T_a)/(T_a + 237.3))$$

The boundary layer resistances are calculated from the latent heat transfer coefficients, h_v. For isolated drops on dry leaf tissue, the heat transfer coefficients are similar to those for hemispheres in free space hh_v where

$$hh_v = 0.66\ R_e^{1/2}\ S^{1/3}\ (D/d_d),$$

R_e is the Reynolds number, S_c is the Schmidt number (0.86), D is the thermal diffusivity of water, ($1.4 * 10^{-7}$ m^2/s), and d_d is the drop diameter ($4.0 * 10^{-3}$ m)[1]. As the drop dries and flattens to a disc, (i.e., drop height, H_d becomes 2% of its diameter) the transfer coefficient changes to hd_v where

$$hd_v = 0.644\ v^{1/2}\ u^{1/2}\ (1-0.055(ux/v)^{1/4})/Sc^{2/3}\ d_d^{1/2})$$

v is the air viscosity ($1.6*10^{-5}$ m^2/s), u is the wind speed in the crop canopy at the height of the drop, and x is the distance of the drop from the edge of the leaf (4.5 cm). The heat transfer to the top of the drop, h_t is $0.93h_v$. The boundary layer resistances are calculated as follows:

$r_{bt} = 1/h_t$, for heat transfer through the top surface of the drop;

$r_{bb} = 1/0.93hd_v$, for heat transfer to the disc under the drop and;

$r_w = 1/h_v$, for evaporation.

Following Barr and Gillespie (1986), the drop was simulated as a cylinder of diameter d_d and height H_d. The surface area was given as

---

[1]This drop size was chosen as a worst case scenario.

$$A_s = \pi(d_d/2)^2 + \pi\, d_d\, H_d.$$

The initial value of the cylinder height was equal to the surface area of the initial hemispheroid to ensure equal evaporation rates. The base area of the drop was

$$A_b = \pi\, (d_d/2)^2.$$

The Reynolds number was calculated as

$$R_e = u^* d_d / v,$$

and the wind speed was computed from weather station data.

Wind speed at the level of the drop, U_{cz}, was computed using an exponential wind profile

$$U_{cz} = U_{ch} \exp\,[r(LAI)]$$

where LAI is the leaf area index, r is the extinction coefficient (0.461), and U_{ch} is the wind speed at the top of the canopy (Zhang and Gillespie, 1990). U_{ch} was derived from hourly wind observations, U_{ws}, taken at ten meters above the surface (see equations for the variables U^*, $U^{*'}$ and y), using the log wind profile and stability corrections (Panofsky and Dutton, 1983).

$$U_{ch} = (U^*/k)*\ln((Z_c - d/z_0)$$

where k is the von Karman constant (0.41), Z_c is the height of the crop, d is the zero plane of displacment (d = 0.67 Z_c), and z_0 is the roughness length (z_0 = 0.13 Z_c). U^* is the friction velocity,

$$U^* = k\, U_{ws} \,/\, (\ln(10/z_0) - \Psi_m)$$

The stability correction, Ψ_m, was calculated from weather station data and physical parameters of the crop canopy using an approximate Obukhov length, L

$$L = -\rho C_p\, T_a\, U^{*'3} \,/\, k*g*H$$

$$U^{*'} = k\, U_{ws} \,/\, \ln(10/z_0)$$

where g is the acceleration due to gravity (9.8 m/s^2) and H is the sensible heat flux.

The calculation of L required an approximation of the whole canopy net radiation, R_{nc}, in order to estimate the canopy sensible heat flux, H. During the day ($R_{nc} > 0$),

$$H = 0.25\ R_{nc},$$

and during the night ($R_{nc} \leq 0$),

$$H = 0.7\ R_{nc}.$$

The whole canopy net radiation was derived from

$$R_{nc} = (1-\alpha_c)R_s + \epsilon L_d - \epsilon\sigma T_a^4$$

where α_c is the albedo of the corn canopy, which can range from 0.16 to 0.25, but it was held constant at 0.23 since the model proved to insensitive to any changes. R_s is incoming solar radiation which is estimated from weather station observations, ϵ is the emissivity of the corn leaf (0.98), σ is the Stefan-Boltzmann constant ($5.6966 * 10^{-8}$), and T_a is the air temperature, in degrees Kelvin, which was computed from weather station data. The downward longwave radiation, L_d was given by the Swinbank approximation

$$L_d = 5.31*10^{-14}\ T_a^6$$

where T_a is the air temperature in degrees Kelvin (Paltridge and Platt, 1976, p. 137).

Following Panofsky and Dutton (1983), if $L < 0$, then

$$\psi_m = 2\ \ln((1+y)/2) + \ln((1+y^2)/2) - 2\arctan(y) + \pi/2$$

where $y = (1-16(10)/L)^{0.25}$.

For other L,

$$\psi_m = -5(10)/L$$

The the net radiation, R_{nd}, is defined by

$$R_{nd} = a_1(1+\alpha)R_{sd} + L_{dd} + L_{ud} - \epsilon\sigma T_w^4\ (A_s+A_b)$$

where L_{dd} and L_{ud} are respectively the absorbed downward and upward long wave flux, a_1 is the absorptivity of the leaf to short wave radiation (held constant at 0.5), α is the underlying albedo (held constant at 0.23), and R_{sd} is the absorbed solar radiation. R_{sd} is a function of the downward short wave flux, R_{sz} and A_b. R_{sz} is defined by

$$R_{sz} = R_s\ \exp(-k_s\ (LAI)/\cos\theta)$$

where k_s is the extinction coefficient (0.656), and θ is the zenith angle of the sun.

$$R_{sd} = (1+\alpha)\ a_1\ R_{sz}\ A_b \text{ and}$$

$$L_{dd} = \epsilon\ L_{dz}\ A_s$$

$$L_{ud} = \epsilon\ L_{uz}\ A_b$$

where $L_{dz} = L_{uz} = \epsilon\sigma(T_a)^4$.

The other variables were defined following Zhang and Gillespie (1990).

Both the wind speed and the radiation required an extinction coefficient in order to derive the appropriate quantity at the height of the droplet in the canopy. In Gillespie and Zhang (1990), the extinction coefficients were provided only for a corn plant of 2.8 meters in height. These coefficients would change from the time the crop first emerges to full development, and initial runs of the simulation suggested that the results were sensitive to this parameter. It was difficult to obtain the correct coefficients for different stages of crop development. In the initial equations the wind speed and the radiation at the drop were functions of the height of the crop, Z_c, and the height of the leaf supporting the droplet, Z.

$$U_{cz} = U_{ch}\ \exp\ [r(Z/Z_c - 1)]$$

$$R_{sz} = R_s\ \exp\ (-k_s\ (Z_c - Z)/\cos\theta)$$

These equations required new extinction coefficients whenever the height of the crop increased. The equations for U_{cz} and R_{sz} were rewritten for the leaf area index (LAI). This technique allowed the use of a constant extinction coefficient, k_s whilst changing the weighting factor ($LAI/\cos\theta$), for the radiation calculation, at different stages of crop development. Similarly, in calculating the wind speed, r is held constant, and the weighting (LAI) changes at different stages of the crop development.

The LAI was deduced by functionally relating LAI to a depth in the canopy The function was estimated from Brown and Covey (1966),

$$LAI = (.02\ DEPTH) - b.$$

Brown and Covey used a maximum LAI of 4.0 which is unrealistic for the corn growing areas in Canada. For these simulations, a maximum LAI of 2.8 was chosen to correspond to the maximum height of the plant (250 centimetres). These maximums are

representative of Canada as a whole although the numbers would vary among the six locations used in this study.

The crop height was determined from the fraction of maximum leaf area, FMXLA (Place and Brown, 1987). Following Place and Brown (1987), the fraction of maximum leaf area is a function of the crop development time (CDT) which in turn is a function of the amount of corn heat units (CHU) (Brown, 1969). The CHU were derived according to Treidl (1977):

$$CHU = \tfrac{1}{4} (1.8\ A + 3.33\ B - 0.084\ B^2)$$

where $A = T_{MIN} - 4.4$; T_{MIN} is the daily minimum temperature in degrees Celsius,

and $B = T_{MAX} - 10$; T_{MAX} is the daily maximum temperature in degrees Celsius.

The starting date for the calculation of CHU occurred when

$T_{MEAN} \geq 12.8°C$ for three successive days (Bhartendu, 1984)

where $T_{MEAN} = \sum T_i/24$, $i = 1,24$.

The CDT is determined by the CHU rating for the cultivar that is being grown,[2]

$$CDT = CHU/(CHU\ rating)*0.6.$$

A CHU rating of 2500 was considered to be representative of most of the locations in this study, although for a synoptic climatology this number would be too low for some Ontario stations. Using the CDT,

$$FMXLA = 1/(1 + \exp(8.73 - 11.3\ CDT)),$$

$$LAI = 2.5 * FMXLA$$

This LAI is not corrected for the level of the droplet. The LAI was used to derive the correct y-intercept on the curve, relating LAI to crop height, to reflect the state of the crop.[3]

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[2]The CHU rating was determined by accumulating CHU's from the planting date until kernel moisture reached a desirable level (Brown, 1986)

[3]Brown and Covey (1966) provided the curve, but it was for a fully developed crop.

A similar formula was used to determine the height of the crop, Z_c (Place, 1984),

$$Z_c = HF * Z_{MAX}$$

where Z_{MAX} is the maximum height (2.8) and HF is a height factor

$$HF = 1/(1 + \exp(8.73 - 13*CDT)).$$

The droplet was placed deep in the canopy (18% of crop height) in order to simulate the worst case scenario. This depth is used to derive the LAI at the level of the drop, and the LAI is used to obtain the extinction coefficients in the wind speed and the radiation calculations.

The simulation model was run after any episode of precipitation including fog. After each time step (1 hour) E_w was converted into an equivalent volume of water that was then subtracted from the volume of the droplet. The energy in watts was converted into joules per hour, $E_{J/hr}$ by multiplying the energy in watts by the number of seconds in an hour,

$$E_{J/hr} = E_w * 3600.$$

This was then divided by 2500 (the number of joules needed to evaporate 1 gram of water) to determine the volume that was lost from the droplet.

The volume was initialized at 30 μl ($0.3*10^{-7}$). The height of the drop, H_d is recalculated by dividing the new volume by double the base area of the drop, (2 A_b)

$$H_d = VOLUME / 2 (d_d/2)^2 \pi.$$

4. MODELLING THE EVAPORATION OF DEW FROM THE LEAF'S SURFACE

The simulation of the evaporation of dew from the surface of a leaf is adapted from Pedro's and Gillespie's utilization of weather station data to estimate dew duration (Pedro and Gillespie, 1982). The dew model was used to calculate the latent heat flux, LE at every time step, such that

$$LE = -(0.622/P)2hw(e_{sl}-e)$$

where hw is the water transfer coefficient (Wm^{-2}) for one side of the leaf, e is defined as e_{DEW}, P is the atmospheric pressure (mb), and e_{sl} is the saturated vapour pressure at the temperature of the leaf, T_{LEAF}. The onset of dew occurred when the latent heat flux was less than zero. The dew episodes ended when the accumulated condensate evaporated during the following day. The evaporation of dew was modelled at the same depth as was the

evaporation of the drop. Even though this is not the optimal level for condensation, neither is it the optimal level for evaporation. However, since this depth represents the worse case scenario for the drop model, the dew was placed there to maintain consistency.

T_{LEAF} was obtained as the difference between T_a and ΔT. The difference between T_a and ΔT was computed to solve for the energy balance of the leaf as suggested by Keith and Sellers (1975) and Norman (1979)

$$T_{num} = \{[aR_s(1+\alpha) + \epsilon R_l - \epsilon\sigma(T_a+273)^4] - (0.622/P)2hw(e_{sa}-e)\}$$

$$T_{den} = [4\epsilon\sigma(Ta+273)^3 + 2hc + (0.622/P)2hws]$$

$$\Delta T = T_{num}/T_{den}$$

where a is the short wave absorptivity of the leaf (0.5), α is the albedo of the surface underneath the leaf (0.17), R_l is the incoming longwave radiation, hc is the heat transfer coefficient, and the other parameters are defined as they were designated previously.

Before the crop reaches full maturity, the canopy is sparse, allowing leaves that are deep in the canopy to receive some direct sunlight. During this part of the growing season, (approximated by May, June, and July), R_l is estimated as in Pedro and Gillespie (1982)[4], using Ångstrom's equation (Ångstrom, 1924) with empirical constants from Morgan et al (1971),

$$R_l = \sigma(T_{ws}^4)[0.82 - 0.25\exp(-2.3 \times 0.094e_{ws})][1 + kc^2]$$

where T_{ws} and e_{ws} are ambient temperature (°K) and vapour pressure (mb) at the weather station and k is a parameter that is dependent on cloud type (Morgan et al, 1971). For a mature crop, leaves deep in the canopy are shaded with no exposure to direct sunlight, therefore in August and September, R_l is given simply by L_{dd}, thereby eliminating the incoming long wave radiation in the equation for ΔT.[5]

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[4]Pedro and Gillespie (1982) assumed that no significant long wave exchange occurred between the lower side of the leaf and the surface below.

[5]Using Ångstrom's equation relatively few dew episodes occurred, and no episode was long enough to contribute to critical episodes of leaf wetness. Using L_{dd}, no dew episodes were recorded.

The parameter k (based on cloud type) was defined for the cloud type variable from the hourly-cloud observations. The parameter k is from Morgan et al (1971). Since k was not defined for every cloud type in the data base it was sometimes necessary to combine different cloud types together. These combinations and the values for k are listed below:

CLOUD TYPE	VALUE FROM HOURLY OBS	K-PARAMETER
Altocumulus	1, 2	.16
Altostratus	3	.2
Cirrus	4, 6	.04
Cirrostratus	5	.08
Cumulonimbus	7, 11	.2
Stratocumulus	13, 14	.22
Stratus Fractus	10	.22
Nimbocumulus	12, 15	.25

The k-parameter was then multiplied by the percentage of cloud cover squared.

The air temperature in the canopy was obtained from a multiple regression equation (Pedro and Gillespie, 1982).

$$T_a = A + B\,T_{ws} + C\,R_n$$

where R_n is the net radiation (W m^{-2})

$$R_n = 0.75\,R_s + 0.95\,R_L - 0.95\,A\,\sigma(T_{ws} + 273)^4$$

$$A = 1.044,\ B = 0.897,\ C = 0.772.$$

In computing T_{LEAF}, it was assumed that any long wave exchange between the surface and the lower side of the leaf was not significant (Pedro and Gillespie, 1982). The radiation at the canopy and the wind speed at the appropriate level were calculated as they were in the drop drying model that was described above.

The heat transfer coefficient, h_c (W m^{-2} $°C^{-1}$), was defined as

$$h_c = 40\ (U_{cz}/D)$$

where D is the effective leaf dimension (10 cm for corn). The water vapour transfer coefficient, h_w (W m^{-2}) is computed from h_c and the ratio of the molecular diffusivities for water vapour and heat

$$h_w = 1.07\ (L/Cp)\ h_c$$

where L is the latent heat of vapourization of water (J Kg^{-1}) and Cp is the specific heat of air (1003 J Kg^{-1} $°C^{-1}$). L is defined by the following equation

$$L = 2.4 + ((1013 - T_a 23.9)/10000.$$

5. WEATHER STATION DATA

While both models were developed and verified with data taken at short time steps (i.e. 15 minutes), this data is not available in sufficient quantity for large scale climate studies. This study used the hourly weather observations from the digital archive of the Canadian Climate Centre (CCC) located at AES in North York, Ontario. The archives encompass the years 1953 to 1988, although the full spectrum is not available for all locations. When it was available, all 36 years were used.

The six locations and the years of data were as follows: Saint John, New Brunswick (1953-1988); Sherbrooke, Quebec (1962-1982); Ste. Agathe, Quebec (1966-1988); Trenton, Ontario (1953-1976); Windsor, Ontario (1953-1988); and Brandon, Manitoba (1959-1988). These locations were chosen to test the behaviour of the simulation across the corn growing region of Canada before undertaking a larger-scale synoptic climatology.

Radiation data are not available to the same degree as other weather observations. The AES national solar radiation network is comprised of 50 observation sites collecting hourly global radiation on a horizontal surface. At a few of these locations sky diffuse irradiance amounts on a horizontal surface are collected. For climate applications, AES supplements and augments these observations with a solar radiation simulation model that estimates solar radiation on a horizontal surface primarily from earth-sun geometry and hourly cloud amounts (Morris and Skinner, 1990).

The AES model incorporates the MAC cloud-layer model (Davies et al, 1984). The root mean square error (RMSE) of the MAC cloud-layer depends on the time scale. For hourly observations the RMSE for global irradiance on a horizontal surface is 30%. The mean bias errors do not depend on the time scale and are about 5%. While with errors of this magnitude, the radiation for a specific place and time is not reliable, the output is suitable for climatology. Morris and Skinner assumed that the climatic statistics generated from the hourly data sets were only a few per cent in error, given the low mean bias error.

The limiting factor in the model may be the resolution of the meteorological input. For example, cloud amounts are observed for an hour, and the models force the assumption that the conditions are exactly the same for that hour (Davies and

McKay, 1989). This criticism is also equally valid for the drop and dew evaporation model, particularly in the timing of precipitation. With the CCC-AES data, precipitation was assumed to begin and end on the hour. While this assumption might not be suitable for estimating leaf wetness duration in real-time, it is not as serious a consideration for climatic studies.

6. RESULTS AND ANALYSIS

Leaf wetness duration was simulated at the six locations for the months May through September (May - August at Brandon, Manitoba), approximating the growing season. Leaf wetness was defined to include the time of evaporation of water, in the form of droplets or dew, from the surface of the leaf and the duration of precipitation. For this simulation the formation of droplets and the dew occurred deep in the canopy (18% of crop height) because these levels are more critical for the development of disease than higher levels that are more exposed to sunlight(ref from Terry Gillespie).[6] Precipitation data included rain, drizzle, and fog. Total leaf wetness, or one complete episode, was the summation of time associated with these different components.

The output was examined for a possible stratification of leaf wetness episodes with average temperature of the episode. This first analysis was disappointing because this type of stratification was not possible. The simulation also generated the probability of the occurrence of each episode, and where applicable, the probability of multiple occurrences of each episode. These probabilities are illustrated graphically for leaf wetness duration of one day or more. The return periods of extreme events were analyzed using the Gumbel distribution. The results and the confidence limits are presented in the form of tables. Surface and upper air synoptic maps were analyzed in order to study the synoptic patterns associated with extreme events of three days or more.

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[6]Even though the formation of dew was inhibited, dew and droplet evaporation were both simulated at this depth in order to maintain consistency in moving between dew events and drop events. If dew had been simulated at a different height, the model could have simulated two episodes of leaf wetness concurrently at the two heights. This could have resulted in situations where leaves were wet at one height and dry at the other, thereby misrepresenting the duration of wetness deeper in the canopy which is more critical for the onset of disease.

The simulation was stratified by month because the phenological stage of the corn crop changes throughout the growing season.[7] It was assumed that it would be also possible to stratify leaf wetness duration with average temperature. This proved not to be the case because the average temperature did not exhibit any observable pattern with the length of the episode. Furthermore, the standard deviations about these means were large indicating too wide a range of temperature variation, associated with any particular episode, to obtain meaningful averages. As well, the lack of any pattern between duration and temperature may be due to other factors that are responsible for the onset of dew (humidity, clear night skies), and other variables acting in unison to control the rate of evaporation of dew and droplets.

The probabilities of one day or more of leaf wetness[8] occurring in any of the five months are displayed graphically (Fig. 1 - 5) for the five months, May through September. The highest and the lowest probability curves are represented by bold lines. The lowest probability of one day of leaf wetness always occurs at Brandon. Brandon was not included in the Figure 5 (or Table 6) because corn is usually harvested in August.

The highest probability of one day of leaf wetness occurs at Ste. Agathe in May and September, followed closely by Saint John. In the summer months the highest probability of one day of leaf wetness occurs at Saint John. In general, the probabilities represented by the particular curve associated with the highest probabilities tends to increase throughout the growing season. During the summer months (June through August) the difference between Saint John and the other stations is greater than the differences between any of the other five stations. For example, during the summer months, at Saint John, one day or more of leaf wetness can occur four times with a probability of 0.56 in June, 0.64 in July, and 0.72 in August (Figures 2 - 4). The next highest probabilities are 0.13 in June and July and 0.22 in August at Ste. Agathe.

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[7]Even though the phenological stages do not correspond exactly to individual months, the calendar provided the same reference point, in time, for each station. As well, the monthly stratification incorporates the change in the extinction coefficients that was required for the simulation of wind speed and radiation within the canopy.

[8]One day of leaf wetness is the critical threshold for many foliar diseases of corn (Andy Teakauz, extension agent, Agriculture Canada Research Station, Winnipeg, Manitoba - personal communication).

For most stations, the probability declined rapidly as the number of occurrences of one day or more of leaf wetness during the month increased. It is important to stress that even though multiple occurrences did occur the associated probability was low. If these results are indicative of the larger picture, then when resources are limited, the focus should be shifted to either those longer episodes that occur with a greater probability or those shorter durations of leaf wetness that are more probable (Figures 6 - 7).[9] However, even if the probability of more than one occurrence is low, a sequence of shorter episodes, if separated by brief dry periods, from a pathological point of view could have the same repercussions as one longer and uninterrupted episode (Andy Teakauz, extension agent, Agriculture Canada Research Station, Winnipeg, Manitoba - personal communication).

The curves could be interpreted qualitatively as the degree of crop management required to prevent disease. Depending on the methods and the philosophy of controlling disease, the costs of regulation may escalate rapidly in June. The lead time required for strategic decisions depends on individual risk behaviours. For example, some growers may decide, that anything that occurs with a probability below 50%[10] in July is not worth planning for in April. Other growers may be more risk averse, and would therefore act accordingly. However all growers might act upon a low probability of leaf wetness if the onset of disease at that particular time could be devastating.

If 50% is chosen as a threshold, then a grower in Saint John would require a greater degree of management than a grower in Brandon, Windsor or Trenton (Figure 8). The graphs imply that leaf wetness would be a greater problem east of Ontario, especially in the Maritimes. It is therefore not surprising that most of the long episodes that were used in the analysis of synoptic maps occurred in the these areas. This regional pattern also emerged in the return periods for extreme episodes of leaf wetness (Tables 1 - 6).

The Gumbel distribution was used to compute the return period of extreme episodes of leaf wetness duration, XT, and the 95% confidence intervals surrounding those values (Tables 1 - 6). XT is given by:

$$XT = MEAN_{XT} + XK * s_{XT}$$

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[9]Figures 7 and 8 illustrate the probability of multiple occurrences of leaf wetness per month of twelve hours or more.

[10]A probability of occurrence equal to 50% is an interesting case because it represents the maximum uncertainty.

where $MEAN_{XT}$ is the mean of the simulated extreme episodes of leaf wetness, s_{XT} is the standard deviation of the simulated extreme values, and XK is a function of the return period (Gumbel, 1958). In general the pattern of the extreme values associated with the return periods corresponded with the geographical pattern that was illustrated in Figures 1 - 5. Just as multiple occurrences of one day or more of leaf wetness were more probable in Saint John, so were extreme values. In May and September the values at Ste. Agathe and Saint John are very close although in September, the extreme values are slightly greater at Ste. Agathe.

Using July as an example, because it is a critical month at each of the six stations, some further observations comparing the stations are possible. Saint John can expect more than two days of leaf wetness every two years and more than three days every five years, in 95% percent of those respective periods. This is critical in Saint John because the low end of confidence intervals are greater than forty-eight and seventy-two hours respectively. Trenton and Windsor can expect one day or more of leaf wetness once every five years whereas this probability is greater at Sherbrooke and Ste. Agathe. At Brandon, the return period for one day or more of leaf wetness, is fifteen years, although a twenty-four hour episode is within the confidence interval of ten years.

7. SYNOPTIC ANALYSIS OF EXTREME EVENTS

The model simulated a number of critical leaf wetness episodes of three days or more in duration. Surface synoptic maps were analyzed for the dates of these events in order to identify those synoptic features that were common in the generation of the extreme episodes.[11] At this stage, any conclusions are somewhat tentative since the interpretations are based on a limited number of episodes, the majority of which occurred at Saint John. Nevertheless, a general synoptic pattern was identified which accounted for all of the longer episodes that were simulated by the model, although there were minor variations in some of the details. All of these long events were exclusively associated with the formation and subsequent evaporation of droplets on the surface of the leaf.[12]

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[11]The times of the available synoptic maps were 1:30 or 7:00 AM E.S.T.

[12]The limited presence of dew resulted from placing the dew at the depth in the canopy corresponding to the worse case scenario for a drop. At this depth, insufficient radiational cooling occurs at night because the shading of the leaf's surface is greater than at higher levels in the canopy.

The synoptic pattern was characterized by one or more low pressure systems supported by an upper trough, which sometimes because of its tilt, resulted in a persistent cut-off. Quite often an extensive frontal system was aligned along the upper trough which slowed down the movement of the system. At times this was further reinforced by a blocking high over the Atlantic Ocean. Some episodes of leaf wetness were characterized by several separate precipitation events separated by brief dry periods, while others were associated with one long period of rain. Episodes were initiated either by rain, or by fog that resulted from a south westerly flow of saturated air. Most of the episodes were terminated by the establishment of a surface high.

8. SUMMARY AND CONCLUSIONS

Models that simulated the evaporation of droplets and dew were combined to simulate leaf wetness duration at six locations using standard weather station observations. The results were stratified by month which highlighted various regional differences. Saint John, New Brunswick emerged as the location that is the most prone to repeated long episodes. Vulnerability to long episodes generally decreased with distance from Saint John. Brandon, Manitoba was least vulnerable to long episodes.

Throughout June, July, and August, the probability of multiple occurrences of a critical threshold of leaf wetness was far greater at Saint John than at the other locations (Figures 1 - 5). During these same months Saint John could expect much greater extremes of leaf wetness at various return periods (Tables 1 - 6). The analysis of return periods revealed a higher frequency of extreme events at Saint John than at the other five stations.

The analysis of the synoptic surface maps indicated that the larger scale synoptic weather patterns, associated with the dates of longer episodes, were consistent with the results of the simulation. This analysis also revealed a major synoptic pattern that appeared to account for the long episodes of leaf wetness duration. This synoptic pattern was characterised by a persistent upper trough, often elongated, and the formation of an upper cut-off low. The majority of the episodes were terminated by a the establishment of a surface high.

The analysis of the six locations has shown that the simulation adequately models leaf wetness episodes deep within the canopy. At this depth, the simulation of dew was inconsequential for occurrences of one day or more of leaf wetness. It is expected that the formation and evaporation of dew would play a more important role at a depth that is closer to the top of the canopy, although this could misrepresent the episode duration at the deeper level.

The regional variation that emerged from various analyses of the simulation results, suggests that a more complete synoptic climatology of leaf wetness for the corn growing area of Canada would be useful for strategic planning to monitor and control plant disease. Presently, the simulation is parameterized for corn, but most of these parameters are related to the extinction coefficients for wind and radiation. Since these coefficients are determined by the LAI, it should be possible to run the simulation for other major agricultural crops in Canada.

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Table 1: The return period of extreme episodes of leaf wetness duration for Saint John, New Brunswick.

SAINT JOHN, NEW BRUNSWICK - MAY

RETURN PERIOD	VALUE	95% CONFIDENCE INTERVAL
2.	36.1	29.1 - 43.1
5.	58.4	45.6 - 71.2
10.	73.2	55.6 - 90.8
15.	81.5	61.0 - 101.9
20.	87.3	64.9 - 109.8
25.	91.8	67.8 - 115.9
30.	95.5	70.2 - 120.8

SAINT JOHN, NEW BRUNSWICK - JUNE

RETURN PERIOD	VALUE	95% CONFIDENCE INTERVAL
2.	47.5	43.4 - 51.5
5.	60.9	53.6 - 68.1
10.	69.7	59.7 - 79.7
15.	74.8	63.1 - 86.4
20.	78.3	65.5 - 91.0
25.	81.0	67.3 - 94.6
30.	83.2	68.8 - 97.5

SAINT JOHN, NEW BRUNSWICK - JULY

RETURN PERIOD	VALUE	95% CONFIDENCE INTERVAL
2.	61.8	54.4 - 69.3
5.	86.7	73.2 - 100.1
10.	103.1	84.6 - 121.6
15.	112.4	90.9 - 133.8
20.	118.8	95.2 - 142.5
25.	123.8	98.6 - 149.1
30.	127.9	101.3 - 154.5

SAINT JOHN, NEW BRUNSWICK - AUGUST

RETURN PERIOD	VALUE	95% CONFIDENCE INTERVAL
2.	52.3	47.5 - 57.2
5.	68.4	59.7 - 77.1
10.	79.1	67.1 - 91.1
15.	85.1	71.1 - 99.0
20.	89.3	74.0 - 104.6
25.	92.5	76.1 - 108.9
30.	95.2	77.9 - 112.4

SAINT JOHN, NEW BRUNSWICK - SEPTEMBER

RETURN PERIOD	VALUE	95% CONFIDENCE INTERVAL
2.	48.4	43.4 - 53.5
5.	65.3	56.2 - 74.4
10.	76.4	63.9 - 89.0
15.	82.7	68.1 - 97.3
20.	87.1	71.1 - 103.1
25.	90.5	73.4 - 107.6
30.	93.3	75.2 - 111.3

Table 2: The return period of extreme episodes of leaf wetness duration for Sherbrooke, Quebec.

SHERBROOKE, QUEBEC - MAY

RETURN PERIOD	VALUE	95% CONFIDENCE INTERVAL
2.	27.2	23.4 - 31.1
5.	37.6	30.4 - 44.8
10.	44.4	34.4 - 54.4
15.	48.3	36.7 - 59.9
20.	51.0	38.2 - 63.8
25.	53.1	39.4 - 66.8
30.	54.8	40.4 - 69.2

SHERBROOKE, QUEBEC - JUNE

RETURN PERIOD	VALUE	95% CONFIDENCE INTERVAL
2.	28.5	24.6 - 32.4
5.	38.8	31.7 - 46.0
10.	45.7	35.7 - 55.7
15.	49.6	38.0 - 61.2
20.	52.3	39.5 - 65.0
25.	54.4	40.7 - 68.0
30.	56.1	41.6 - 70.5

SHERBROOKE, QUEBEC - JULY

RETURN PERIOD	VALUE	95% CONFIDENCE INTERVAL
2.	24.6	21.8 - 27.5
5.	32.3	27.0 - 37.6
10.	37.4	30.0 - 44.8
15.	40.3	31.6 - 48.9
20.	42.3	32.8 - 51.7
25.	43.8	33.7 - 53.9
30.	45.1	34.4 - 55.8

SHERBROOKE, QUEBEC - AUGUST

RETURN PERIOD	VALUE	95% CONFIDENCE INTERVAL
2.	28.3	24.4 - 32.3
5.	38.9	31.6 - 46.2
10.	45.8	35.7 - 56.0
15.	49.8	38.0 - 61.6
20.	52.5	39.5 - 65.5
25.	54.6	40.7 - 68.6
30.	56.4	41.7 - 71.0

SHERBROOKE, QUEBEC - SEPTEMBER

RETURN PERIOD	VALUE	95% CONFIDENCE INTERVAL
2.	33.7	30.5 - 36.8
5.	42.1	36.3 - 48.0
10.	47.7	39.6 - 55.8
15.	50.8	41.4 - 60.3
20.	53.0	42.6 - 63.4
25.	54.7	43.6 - 65.9
30.	56.1	44.4 - 67.9

Table 3: The return period of extreme episodes of leaf wetness duration for Ste. Agathe, Quebec.

STE. AGATHE, QUEBEC - MAY

RETURN PERIOD	VALUE	95% CONFIDENCE INTERVAL
2.	35.3	27.6 - 43.0
5.	56.7	42.5 - 71.0
10.	70.9	51.1 - 90.7
15.	78.9	55.9 - 102.0
20.	84.6	59.2 - 109.9
25.	88.9	61.7 - 116.0
30.	92.4	63.8 - 121.0

STE. AGATHE, QUEBEC - JUNE

RETURN PERIOD	VALUE	95% CONFIDENCE INTERVAL
2.	30.2	26.4 - 34.1
5.	40.8	33.8 - 47.9
10.	47.9	38.1 - 57.7
15.	51.9	40.4 - 63.3
20.	54.6	42.1 - 67.2
25.	56.8	43.3 - 70.2
30.	58.5	44.4 - 72.7

STE. AGATHE, QUEBEC - JULY

RETURN PERIOD	VALUE	95% CONFIDENCE INTERVAL
2.	26.7	22.6 - 30.9
5.	38.2	30.6 - 45.9
10.	45.9	35.2 - 56.5
15.	50.2	37.8 - 62.5
20.	53.2	39.6 - 66.8
25.	55.5	40.9 - 70.1
30.	57.4	42.0 - 72.7

STE. AGATHE, QUEBEC - AUGUST

RETURN PERIOD	VALUE	95% CONFIDENCE INTERVAL
2.	34.9	30.6 - 39.2
5.	46.9	38.9 - 54.8
10.	54.8	43.7 - 65.8
15.	59.3	46.4 - 72.1
20.	62.4	48.3 - 76.5
25.	64.8	49.7 - 79.9
30.	66.8	50.8 - 82.7

STE. AGATHE, QUEBEC - SEPTEMBER

RETURN PERIOD	VALUE	95% CONFIDENCE INTERVAL
2.	47.2	40.8 - 53.5
5.	64.8	53.1 - 76.5
10.	76.5	60.2 - 92.7
15.	83.0	64.1 - 102.0
20.	87.6	66.8 - 108.4
25.	91.2	68.9 - 113.5
30.	94.1	70.6 - 117.5

Table 4: The return period of extreme episodes of leaf wetness duration for Trenton, Ontario.

TRENTON, ONTARIO - MAY

RETURN PERIOD	VALUE	95% CONFIDENCE INTERVAL
2.	22.5	19.9 - 25.1
5.	29.9	25.1 - 34.8
10.	34.8	28.1 - 41.5
15.	37.6	29.8 - 45.4
20.	39.5	31.0 - 48.1
25.	41.0	31.8 - 50.2
30.	42.2	32.6 - 51.9

TRENTON, ONTARIO - JUNE

RETURN PERIOD	VALUE	95% CONFIDENCE INTERVAL
2.	21.5	18.5 - 24.6
5.	30.2	24.6 - 35.9
10.	35.9	28.1 - 43.8
15.	39.2	30.1 - 48.3
20.	41.5	31.4 - 51.5
25.	43.2	32.5 - 53.9
30.	44.6	33.3 - 55.9

TRENTON, ONTARIO - JULY

RETURN PERIOD	VALUE	95% CONFIDENCE INTERVAL
2.	21.2	18.8 - 23.7
5.	28.1	23.6 - 32.6
10.	32.7	26.4 - 39.0
15.	35.3	28.0 - 42.6
20.	37.1	29.1 - 45.1
25.	38.5	29.9 - 47.1
30.	39.6	30.6 - 48.6

TRENTON, ONTARIO - AUGUST

RETURN PERIOD	VALUE	95% CONFIDENCE INTERVAL
2.	22.9	20.1 - 25.7
5.	30.7	25.6 - 35.8
10.	35.9	28.8 - 43.0
15.	38.8	30.6 - 47.1
20.	40.9	31.8 - 50.0
25.	42.5	32.7 - 52.2
30.	43.8	33.5 - 54.0

TRENTON, ONTARIO - SEPTEMBER

RETURN PERIOD	VALUE	95% CONFIDENCE INTERVAL
2.	29.4	24.3 - 34.5
5.	43.7	34.4 - 53.0
10.	53.1	40.2 - 66.1
15.	58.5	43.4 - 73.5
20.	62.2	45.7 - 78.8
25.	65.1	47.4 - 82.8
30.	67.4	48.8 - 86.1

Table 5: The return period of extreme episodes of leaf wetness duration for Windsor, Ontario.

WINDSOR, ONTARIO - MAY

RETURN PERIOD	VALUE	95% CONFIDENCE INTERVAL
2.	28.1	23.6 - 32.5
5.	42.9	34.9 - 51.0
10.	52.8	41.7 - 63.8
15.	58.3	45.4 - 71.2
20.	62.2	48.1 - 76.3
25.	65.2	50.1 - 80.3
30.	67.6	51.7 - 83.5

WINDSOR, ONTARIO - JUNE

RETURN PERIOD	VALUE	95% CONFIDENCE INTERVAL
2.	20.0	18.3 - 21.7
5.	25.6	22.6 - 28.7
10.	29.4	25.1 - 33.6
15.	31.5	26.6 - 36.4
20.	33.0	27.6 - 38.3
25.	34.1	28.3 - 39.9
30.	35.0	29.0 - 41.1

WINDSOR, ONTARIO - JULY

RETURN PERIOD	VALUE	95% CONFIDENCE INTERVAL
2.	19.8	18.1 - 21.4
5.	25.2	22.3 - 28.2
10.	28.9	24.8 - 33.0
15.	30.9	26.2 - 35.7
20.	32.4	27.1 - 37.6
25.	33.5	27.9 - 39.0
30.	34.4	28.5 - 40.2

WINDSOR, ONTARIO - AUGUST

RETURN PERIOD	VALUE	95% CONFIDENCE INTERVAL
2.	24.7	20.9 - 28.5
5.	37.3	30.5 - 44.2
10.	45.7	36.3 - 55.1
15.	50.4	39.5 - 61.3
20.	53.7	41.7 - 65.7
25.	56.2	43.4 - 69.1
30.	58.3	44.8 - 71.8

WINDSOR, ONTARIO - SEPTEMBER

RETURN PERIOD	VALUE	95% CONFIDENCE INTERVAL
2.	28.4	24.5 - 32.2
5.	41.2	34.3 - 48.2
10.	49.7	40.1 - 59.3
15.	54.5	43.4 - 65.6
20.	57.9	45.7 - 70.1
25.	60.5	47.4 - 73.5
30.	62.6	48.8 - 76.3

Table 6: The return period of extreme episodes of leaf wetness duration for Brandon, Manitoba.

BRANDON, MANITOBA - MAY

RETURN PERIOD	VALUE	95% CONFIDENCE INTERVAL
2.	17.0	13.5 - 20.5
5.	27.8	21.4 - 34.1
10.	34.9	26.1 - 43.7
15.	39.0	28.7 - 49.2
20.	41.8	30.6 - 53.0
25.	43.9	31.9 - 56.0
30.	45.7	33.1 - 58.4

BRANDON, MANITOBA - JUNE

RETURN PERIOD	VALUE	95% CONFIDENCE INTERVAL
2.	16.7	14.0 - 19.5
5.	25.2	20.2 - 30.1
10.	30.7	23.9 - 37.6
15.	33.9	25.9 - 41.8
20.	36.1	27.3 - 44.8
25.	37.8	28.4 - 47.1
30.	39.1	29.3 - 49.0

BRANDON, MANITOBA - JULY

RETURN PERIOD	VALUE	95% CONFIDENCE INTERVAL
2.	14.7	13.2 - 16.2
5.	19.4	16.6 - 22.1
10.	22.5	18.7 - 26.3
15.	24.2	19.8 - 28.7
20.	25.5	20.6 - 30.3
25.	26.4	21.2 - 31.6
30.	27.2	21.7 - 32.7

BRANDON, MANITOBA - AUGUST

RETURN PERIOD	VALUE	95% CONFIDENCE INTERVAL
2.	16.6	14.2 - 19.0
5.	24.0	19.6 - 28.3
10.	28.9	22.8 - 34.9
15.	31.6	24.6 - 38.6
20.	33.5	25.9 - 41.2
25.	35.0	26.8 - 43.3
30.	36.3	27.6 - 44.9

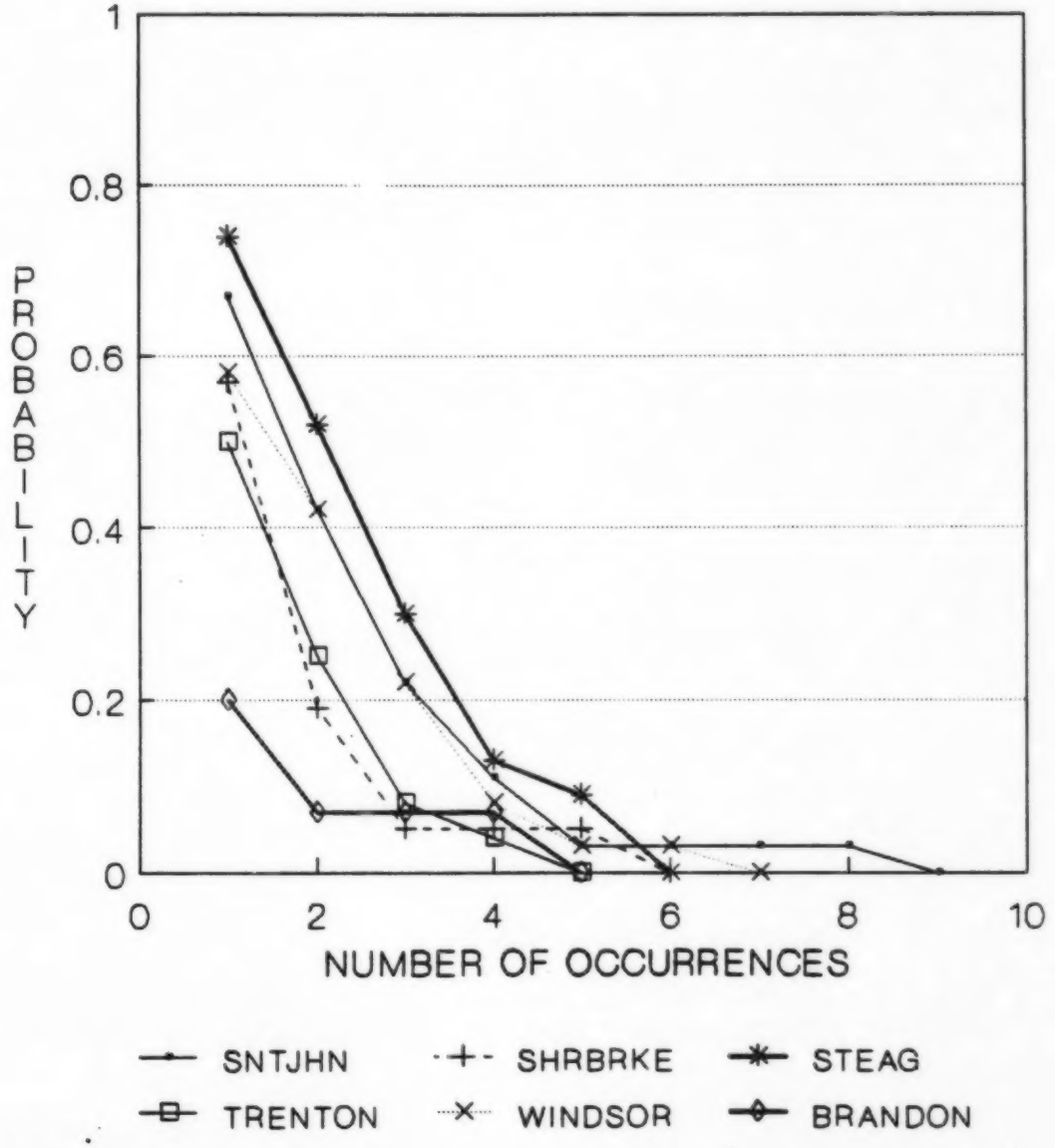

Fig. 1. Probability of 24 hours or more of leaf wetness in May for each of the six climate stations. The thick curves represent the highest and lowest probabilities at Ste-Agathe and Brandon, respectively.

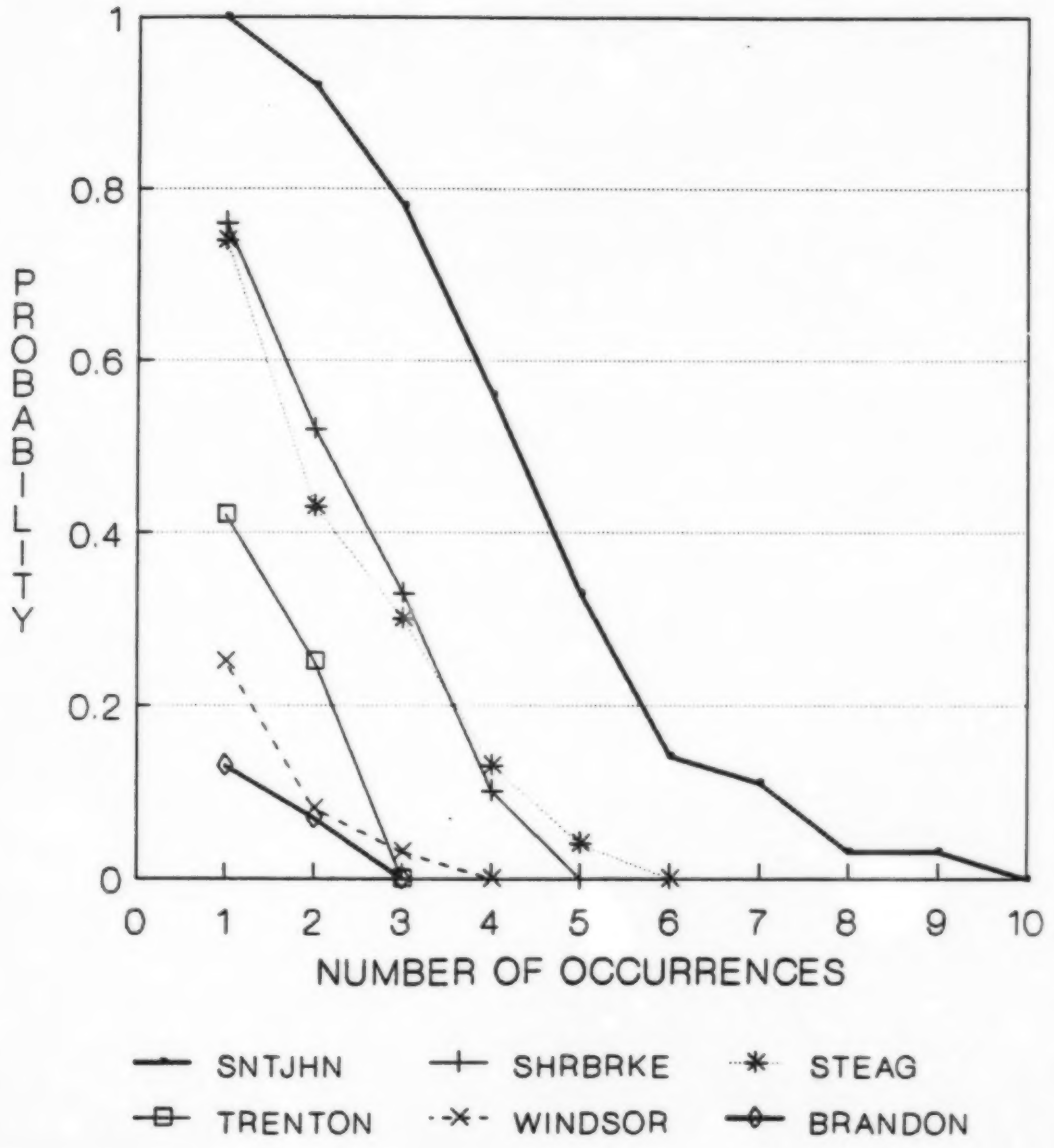

Fig. 2. Probability of 24 hours or more of leaf wetness in June for each of the six climate stations. The thick curves represent the highest and lowest probabilities at Saint John and Brandon, respectively.

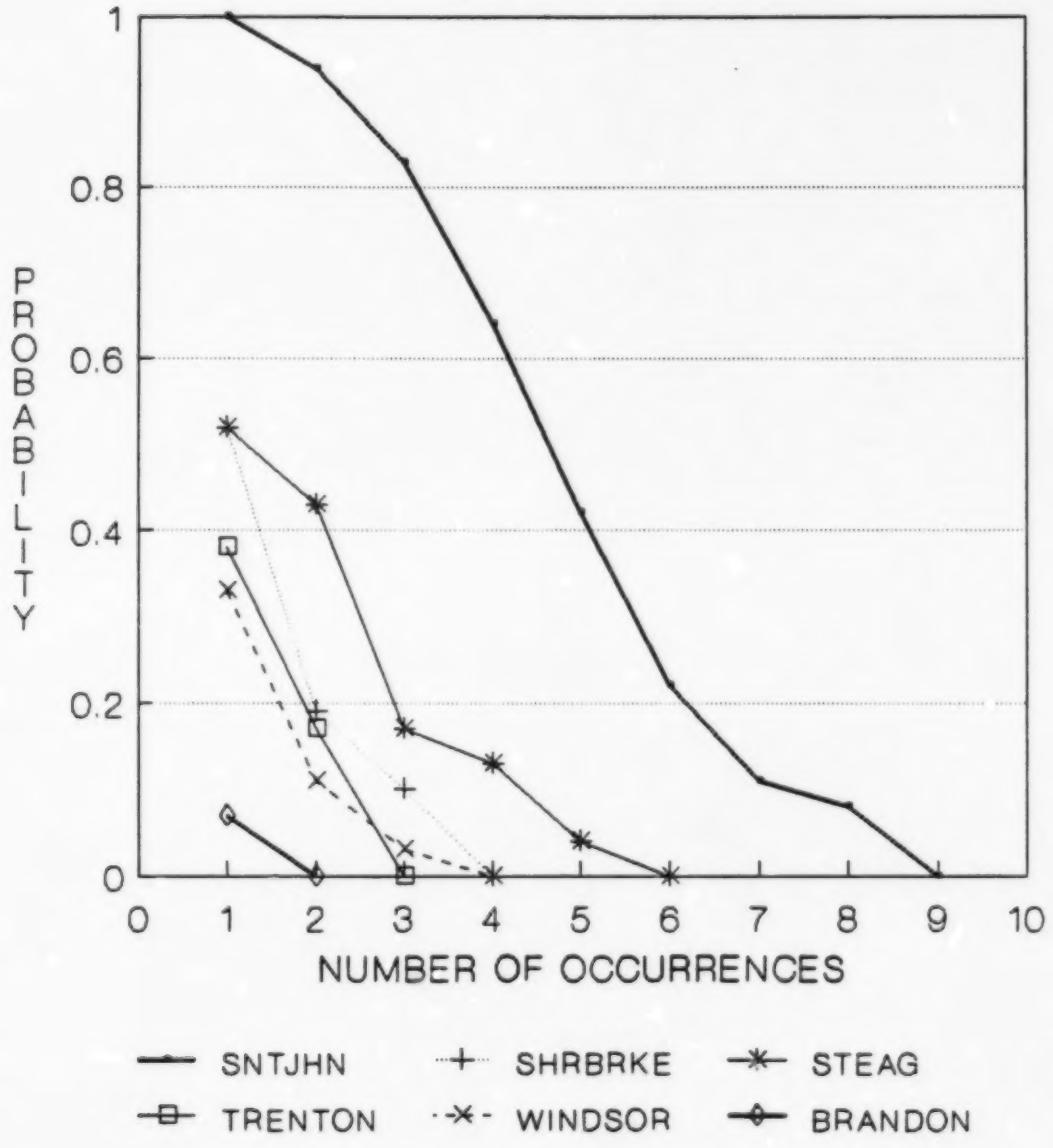

Fig. 3. Probability of 24 hours or more of leaf wetness in July for each of the six climate stations. The thick curves represent the highest and lowest probabilities at Saint John and Brandon, respectively.

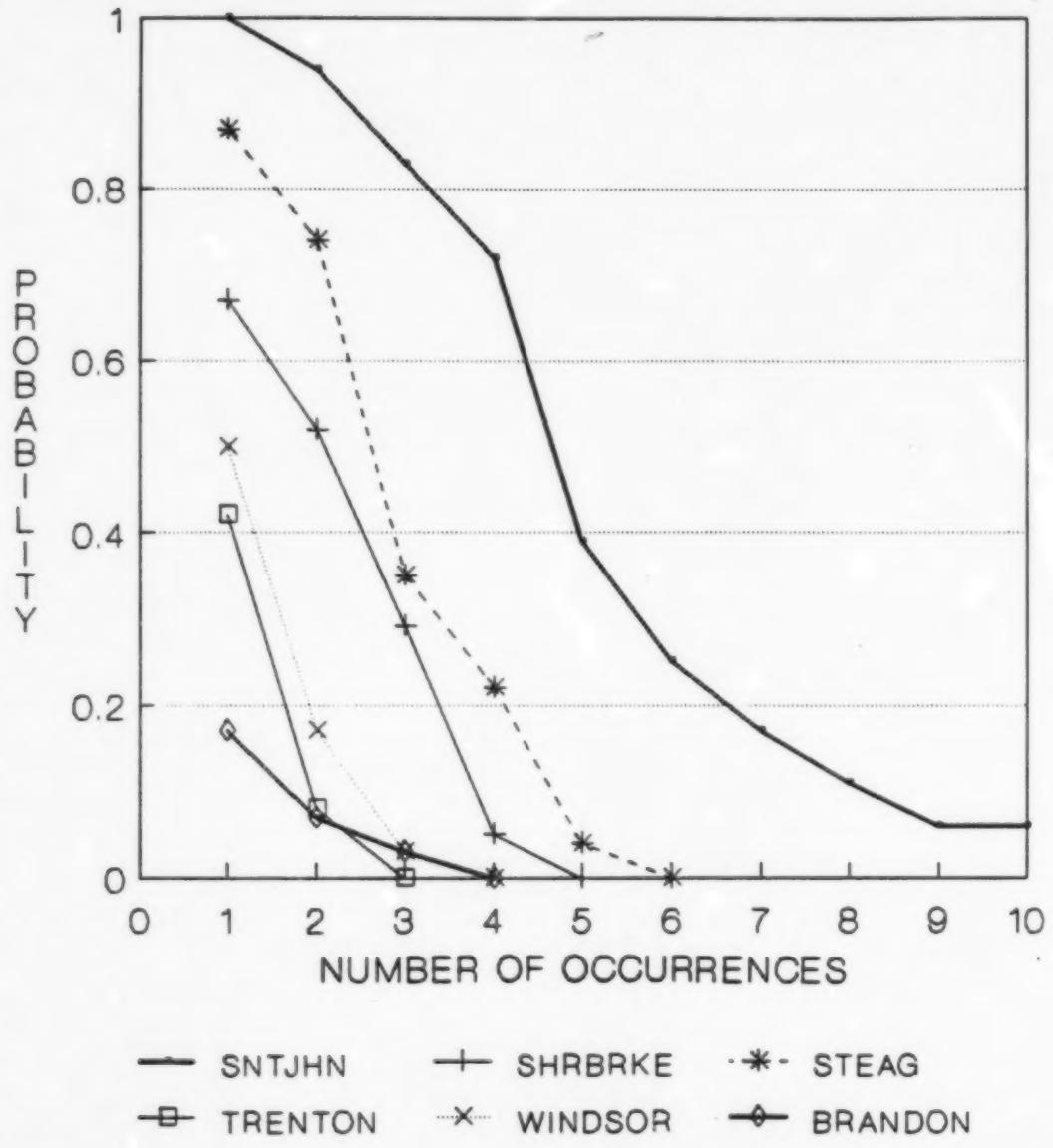

Fig. 4. Probability of 24 hours or more of leaf wetness in August for each of the six climate stations. The thick curves represent the highest and lowest probabilities at Saint John and Brandon, respectively.

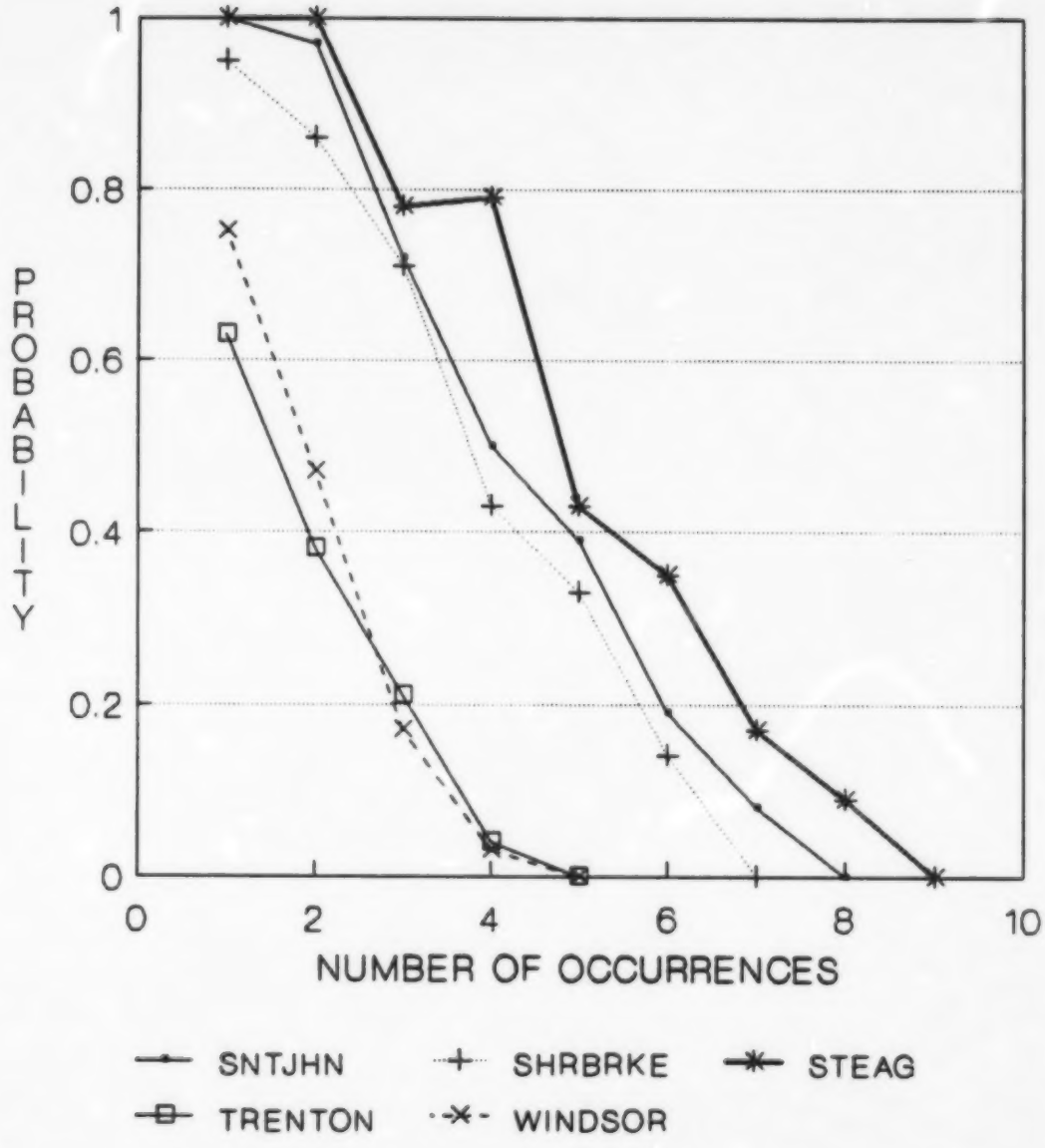

Fig. 5. Probability of 24 hours or more of leaf wetness in September for five of the climate stations. The thick line represents the highest probability at Ste-Agathe.

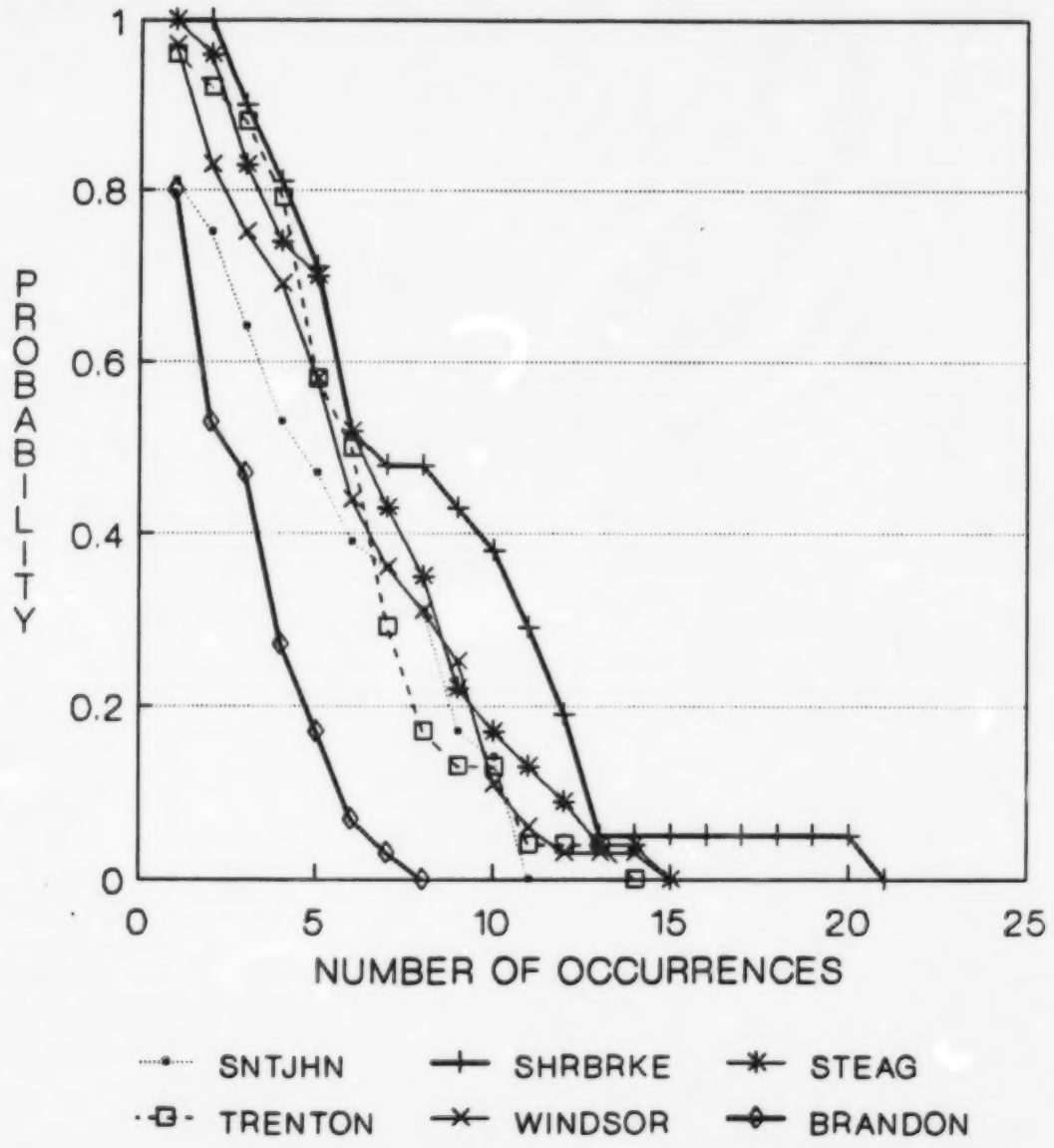

Fig. 6. Probability of 12 hours or more of leaf wetness in May for each of the six climate stations. The thick curves represent the highest and lowest probabilities at Sherbrooke and Brandon, respectively.

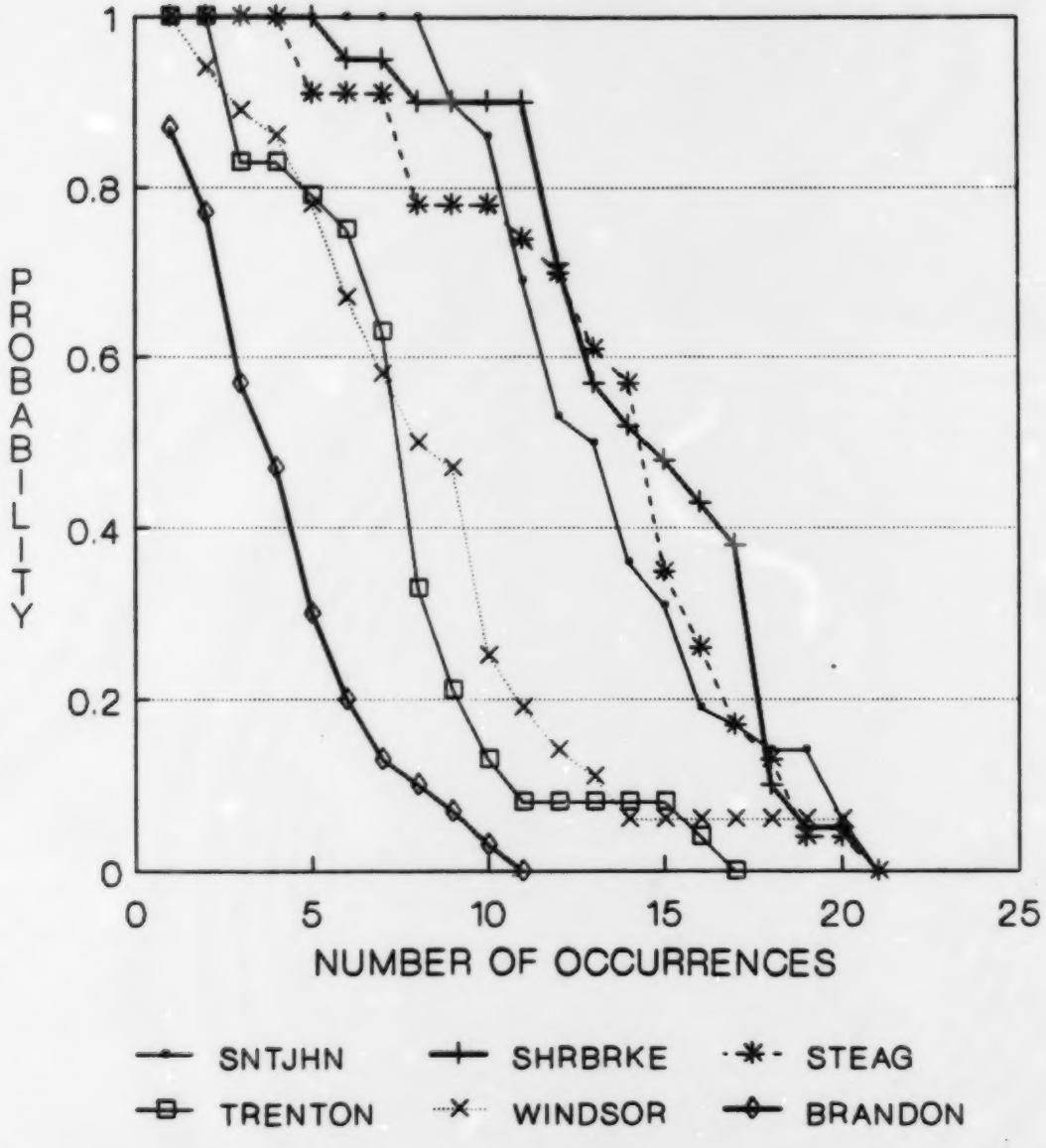

Fig. 7. Probability of 12 hours or more of leaf wetness in August for each of the six climate stations. The thick curves represent the highest and lowest probabilities at Windsor and Brandon, respectively.

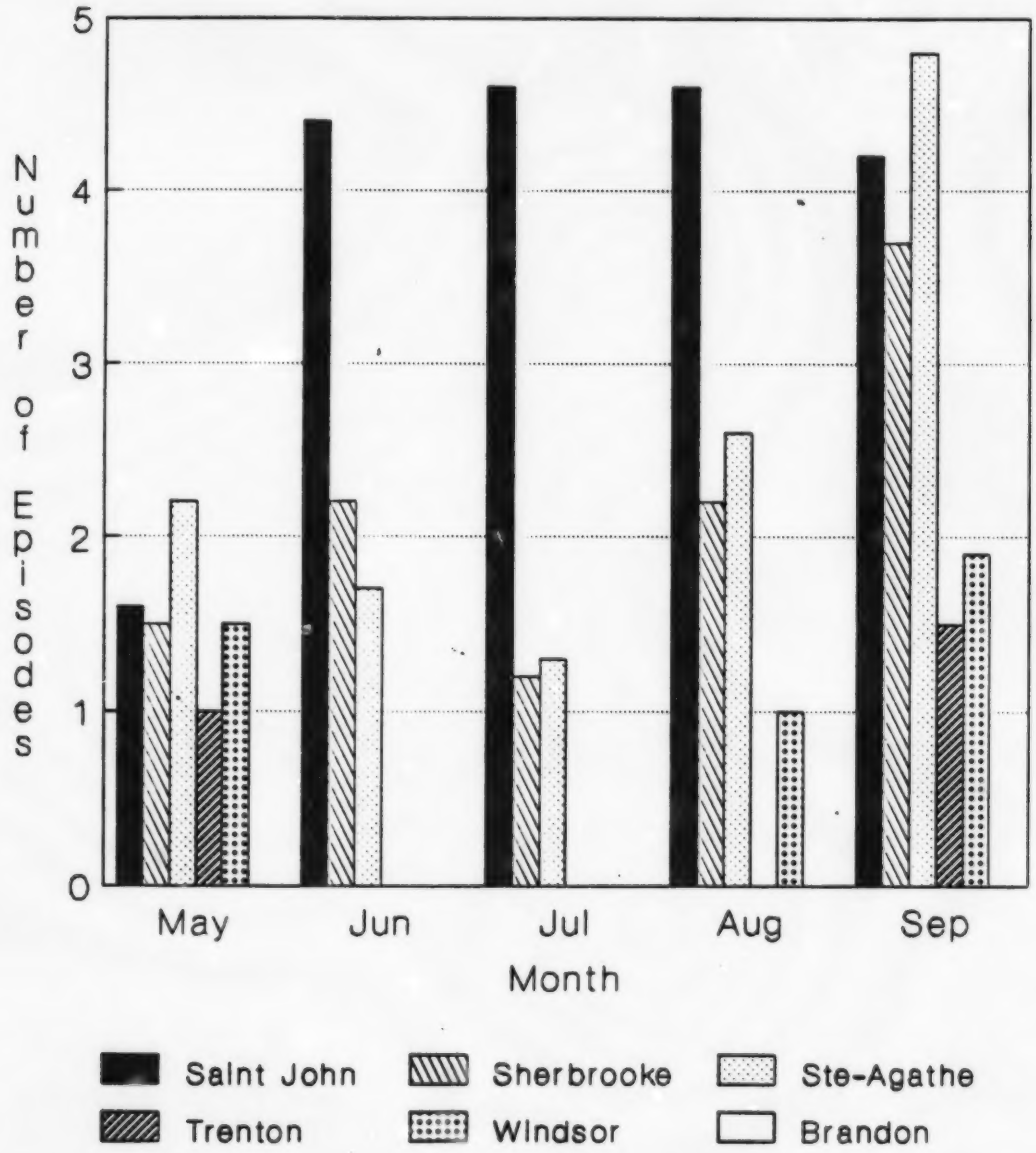

Fig. 8. The number of leaf wetness episodes of 24 hours in length that are expected to occur at each station, from May through August with a probability of p = 0.5.